BBC RD 1978/2

BBC

RESEARCH DEPARTMENT

1974
THE QUEEN'S AWARD
TO INDUSTRY

REPORT

Sampling frequencies and structures for solid state image sensing in broadcasting

G.M. Le Couteur, B.Sc., A.K.C.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

January 1978

BBC RD 1978/2
UDC 621.385.832.5:
621.391.837.43

SAMPLING FREQUENCIES AND STRUCTURES FOR SOLID STATE IMAGE SENSING IN BROADCASTING

G.M. Le Couteur, B.Sc., A.K.C.

Summary

Solid State Image Sensors are unlike present day camera tubes in that the light sensitive region is organised as discrete light sensitive elements each of which give rise to a distinct sample in the output video waveform.

Because of this spatial sampling structure, and the resultant sampled nature of the signal, it has been suggested that there might be an advantage if the sampling frequency for the sensor were chosen to be the same as that used in any subsequent digital processing or signal distribution.

This report examines the factors affecting the choice of sampling frequencies and structures for solid state sensors, and concludes that in general there is no need to link the two sampling frequencies, and that, indeed, it will often be undesirable to do so.

Issued under the authority of

G D Monteath

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

January 1978

(PH-183)

SAMPLING FREQUENCIES AND STRUCTURES FOR SOLID STATE IMAGE SENSING IN BROADCASTING

Section	Title	Page
	Summary	Title Page
1.	Introduction	1
2.	The sampling structures of solid state image sensors	1
3.	Using solid state sensors as unsampled, analogue picture sources	4
	3.1. Efficiency of removal of frequency components at the sensor sampling frequency	4
	3.2. Alias components caused by the sampling structure of the sensor	4
	3.3. Experimental results so far	6
4.	Conclusions and recommendations	6
5.	References	7
	Appendix	7

SAMPLING FREQUENCIES AND STRUCTURES FOR SOLID STATE IMAGE SENSING IN BROADCASTING

G.M. Le Couteur, B.Sc., A.K.C.

1. Introduction

It is generally accepted that solid state image sensors will eventually replace camera tubes as the means of converting an image into a television signal in broadcast television cameras. There is also a potential application for line sensors as a means of scanning film in telecine machines.

Predictions as to the likely date of introduction of these techniques to broadcast vary somewhat, and this is due to the rather uncertain rate of progress of this technology in the future, but current informed estimates place the date of introduction of solid state sensors into broadcasting within the next 5 to 10 years.

The introduction of digital processing techniques into studios and distribution centres is taking place on a somewhat shorter time scale. One of the questions now receiving consideration is the sampling frequency of such digital processing and distribution and it has been suggested that the most desirable number of elements in a solid state sensor may be linked with the choice of an optimum sampling structure for digital signal processing and that, indeed, the two might share a commong sampling frequency.

Whilst a shared common frequency may seem to be desirable on the grounds of simplicity and the avoidance of unwanted frequency components related to the frequency difference between the two sampling structures, there may be irreconcilable differences between the interests of solid state sensors (resolution, aliasing, speed of clocking, orthogonality of sampling structures) and the interests of digital signal processing and distribution in which sampling frequencies are likely to be subcarrier related in PAL and NTSC countries and having other structures in SECAM countries.

This report will particularly examine the sampling structures which are possible with solid state sensors, the complexity involved in achieving them, and the influence, if any, which subsequent digital processing should have on the design of sensors.

2. The sampling structures of solid state image sensors

The sampling structures of solid state sensors are subject to certain limitations which arise from the physical properties of the devices and the methods which have so far been developed to provide internal self-scanning. Certain features can be listed which, although not necessarily inherent, have, for very good reasons, been adopted in all sensors so far built. These are as follows:—

(a) The arrangement of Solid State Image Sensor targets in geometrically ordered light sensitive elements or photosites as opposed to homogeneous targets as found in most camera tubes.

(b) The adoption of photosites essentially fixed in space.

(c) The arrangement of these photosites in an orthogonal structure.

The arrangement of sensor targets in geometrically ordered photosites is inherent to the concept of a self-scanned sensor. The fact that these should remain permanently fixed in space is highly desirable and may seem self evident, although for completeness it should be said that the concept of a moveable light sensitive element is not as impossible as may appear, since in CCD's, the centres of such elements are defined by the position and shape of potential wells formed underneath the CCD electrodes, and it is possible to alter their shape and position by varying the potentials on the electrodes.[1] Slight displacement of photosites is carried out to a limited extent in a certain type of sensor to achieve interlace,* however large movement of photosites is no more than a theoretical possibility

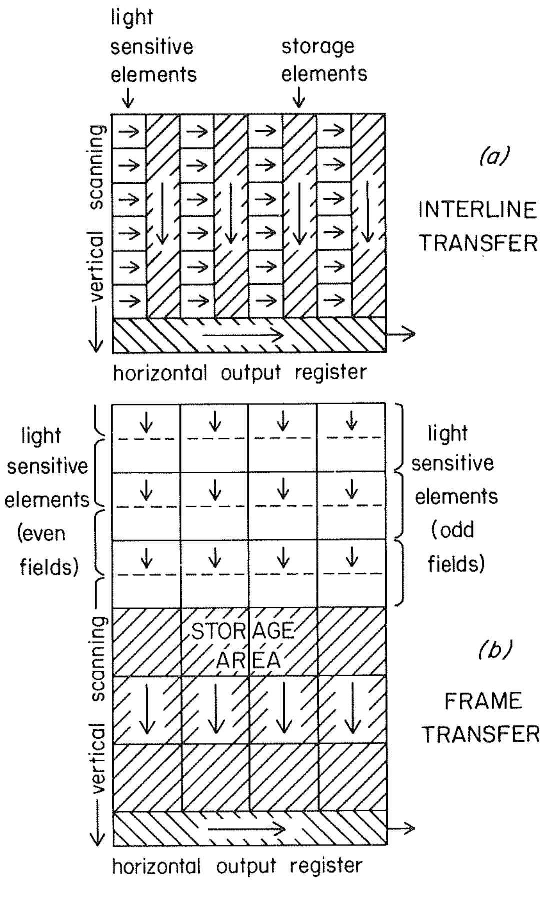

light sensitive elements
storage elements
vertical scanning
(a)
INTERLINE TRANSFER
horizontal output register
light sensitive elements (even fields)
light sensitive elements (odd fields)
STORAGE AREA
vertical scanning
(b)
FRAME TRANSFER
horizontal output register

Fig. 1
(*a*) Layout of an 'Interline Transfer' type CCD
(*b*) Layout of a 'Field Transfer' type CCD

* See Appendix.

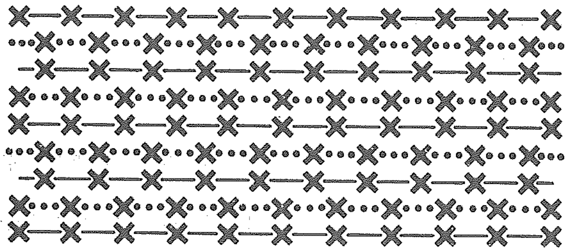


Fig. 2 - Line interlaced sampling structure

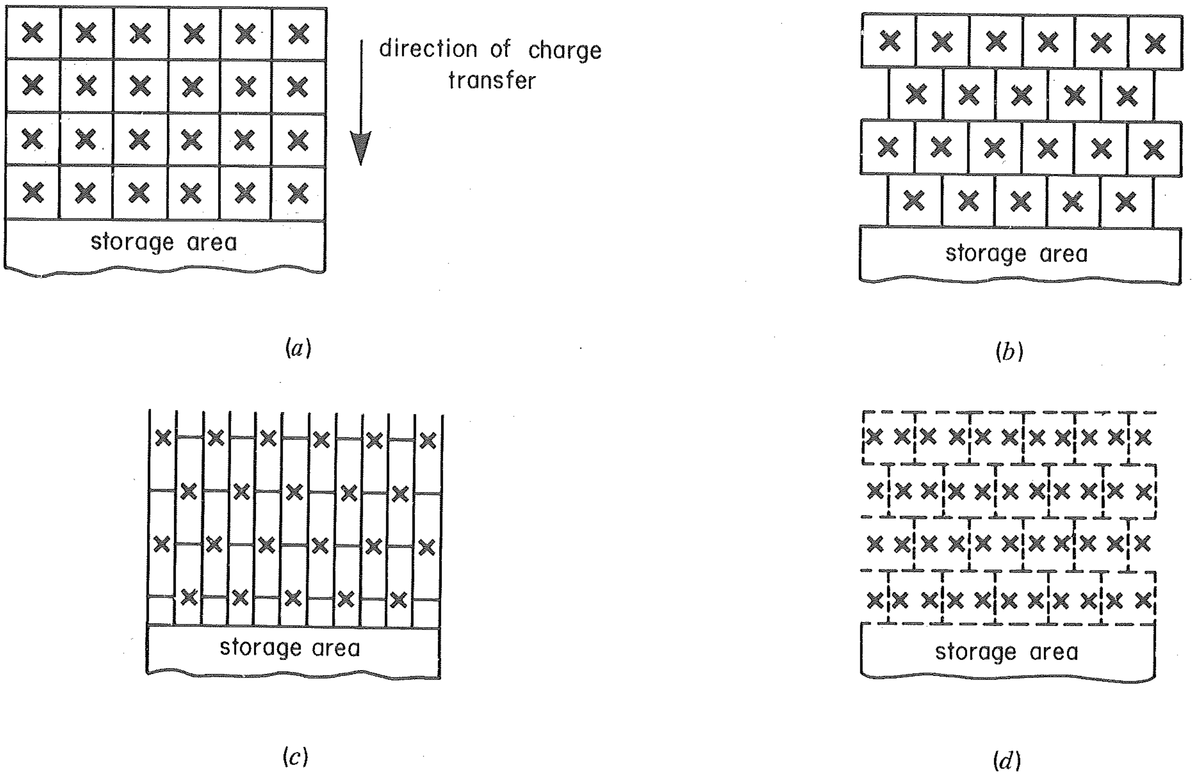
and in practical sensors the need for fixed sampling sites is dictated by the internal arrangements for self-scanning. Not only does the self-scanning organisation call for fixed sampling sites, it also provides strong arguments for wanting these sites to be arranged in an orthogonal structure.

In CCD's two principal methods of internal self-scanning have emerged. There are illustrated in Fig. 1(*a*), (*b*). Those readers who are unfamiliar with the distinction between these two methods will find an explanation in Appendix A. Both share the common feature that the information is transferred down the sensor along columns of parallel transfer registers. This is possible only because the light sensitive elements themselves are arranged in rows and columns, that is, in an orthogonal structure.

In present day sensors, therefore, the sampling of the optical image is such that the sampling frequencies which can be used will either have to be at multiples of line frequency, or if a discontinuous sampling sequence is used, the frequency can be any desired frequency with the phase adjusted at the beginning of each line to make the sample phases the same on each line. Any departure from line locked or line triggered sampling will produce a video signal which will in general contain positional geometric errors, either stationary or moving, depending on the precise sampling frequency. This obviously rules out the use of certain PAL subcarrier-related sampling frequencies unless some future extension of the technology yields sensors with moveable light sensitive elements.

Whilst in general the departure from an orthogonal sampling structure seems to be undesirable, there are special cases of non-orthogonality which might conceivably be accommodated by a special design of the sensor. In particular, one structure which is being considered for use for the sampling of the luminance component in a Y,U,V, digital transmission 'package' is the line interlaced pattern illustrated in Fig. 2. The sampling pulses are line triggered but displaced by 180° on alternate field lines.

It has been suggested that the possibility of designing a solid state sensor with such a sampling structure should be considered. Some of the problems facing the designer of such a sensor can be understood by reference to Fig. 3(*a*) which shows the positions and active areas of the photosites on a conventional orthogonal CCD of the frame transfer type. (The ensuing arguments will also be



(*a*) (*b*)

(*c*) (*d*)

Fig. 3

(*a*) Positions of photosites in a frame transfer CCD sensor (*b*) Re-arrangement of photosites to give 'line interlaced' sampling strucutre

(*c*) Arrangement of photosites necessary to permit vertical charge transfer

(*d*) High resolution orthogonal structure being used to provide line interlaced sampling by means of interpolation applicable, with some slight accommodation on the part of the reader, to sensors of the interline transfer type.) The direction of charge transfer into the temporary storage region is downwards.

Fig. 3(*b*) shows a sensor with the same element density, but with a line interlaced structure. It is clear that charge transfer channels no longer exist for the transfer of charge vertically. One way of overcoming this difficulty is to change the shape of the photosites to the form shown in Fig. 3(*c*). Such an arrangement would allow the vertical transfer of charge, but would in effect require twice the packing density of elements horizontally. If the technology permitted packing densities of that order, a preferable solution might well be to make an orthogonal structure which could then be subsequently signal processed using interpolation techniques to give effective apertures of the shape shown dotted in Fig. 3(*d*). The realisation of this type of high resolution sensor is, however, unlikely for a great many years.

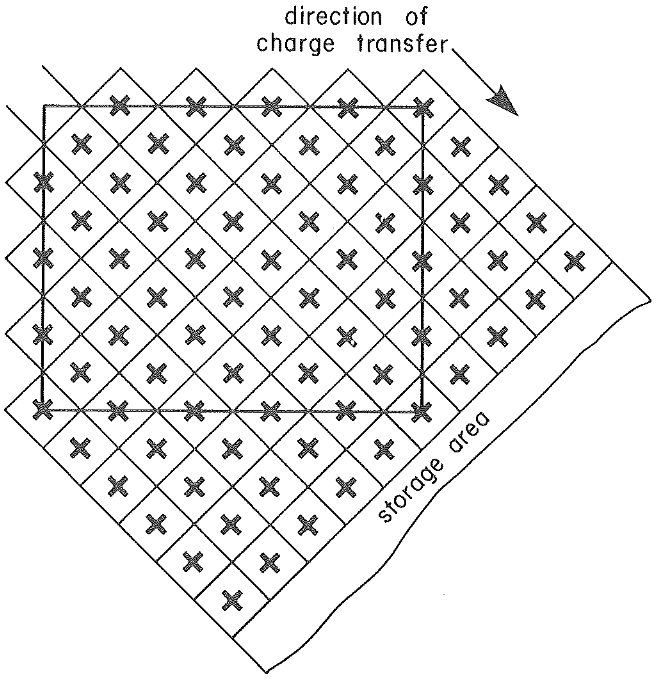


Fig. 4 - Frame transfer CCD rotated through 45° to demonstrate how a line interlaced structure might be formed

A further approach which merits possible thought is best illustrated by visualising an orthogonal sensor being rotated through 45°. The sampling sites will then lie in an interlaced pattern as shown in Fig. 4. Charge transfer then takes place diagonally. As it stands, this is a poor way of using a CCD, because a large part of the available sensitive area is not used, the information which emerges is in the wrong sequence, and the attainment of interlace seem to present rather serious problems. However, it may be that the use of CID* technology, which features random access to the charge on each photosite, could be modified to work along these lines, but it is clear that any departure from the presently accepted orthogonality of sampling sites will need to be justified on very strong theoretical and economic grounds, before it could be considered by sensor manufacturers.

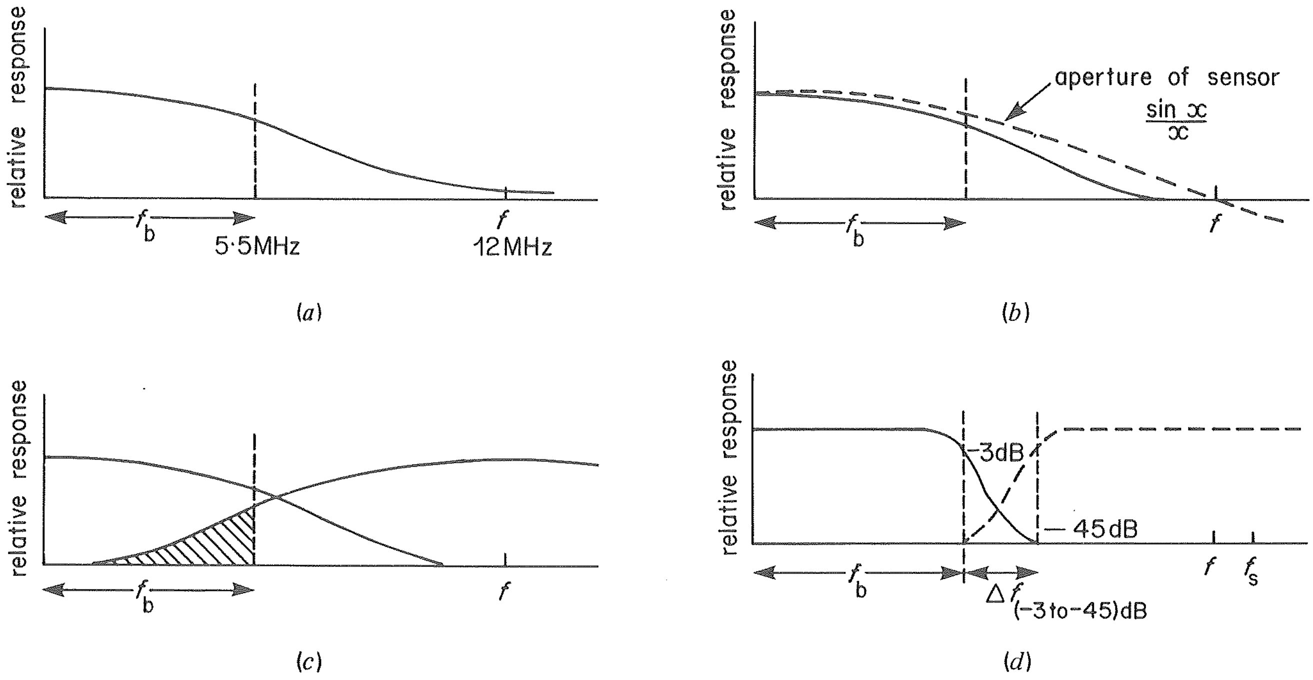


Fig. 5

(*a*) Spectral distribution of scene as modified by the optics of the camera

(*b*) Further modification caused by the aperture of the sensor, assumed $(\sin x)/x$

(*c*) Formation of alias components by sampling at a frequency f; aliased components shown hatched

(*d*) Characteristics of the filter necessary to avoid further alias components caused by sampling at a second frequency f_s

---

* Charge Injection Device.

3. Using solid state sensors as unsampled, analogue picture sources

Whether or not the structure of solid state sensors can be matched to certain line locked sampling structures, it seems almost certain that in PAL countries, signal processing and/or distribution will take place on non-line locked PAL subcarrier related frequencies. It is therefore relevant to consider the extent to which the output of a solid state sensor can be made to look like an unsampled, analogue source. There are two aspects to the question which have to be considered, namely:

(a) The effect of optical pre-filtering (or the absence of it) on the signal produced by the sensor, and the alias components thereby produced.

(b) The efficiency of removal of frequency components consisting of sidebands of the sensor sampling frequency. This is important because if any such components are left, they will be converted into alias components in the second sampling process.

Fig. 5 illustrates the situation. In Fig. 5(*a*) the spectrum of the optical image is shown. This is likely to be approximately Gaussian and as an example it is assumed that the required bandwidth is 5·5 MHz, that the energy has become negligible by about 11 MHz, and that the sampling frequency of the sensor, f is 12 MHz.

Fig. 5(*b*) shows the modification to the spectrum caused by the aperture of the sensing elements. This aperture will be a function of the geometric layout of the light sensing elements and of the shape of the potential wells beneath them, but the figure illustrates the effect of a simple rectangular aperture of width equal to the sample pitch; this gives a $(\sin x)/x$ spectrum with the first zero at the sensor sampling frequency. The overall spectral response is given by this $(\sin x)/x$ function multiplied by the curve in Fig. 5(*a*).

Fig. 5(*c*) illustrates the well-known convolution of the spectrum with that of the sensor sampling waveform, and shows the consequent overlap between adjacent orders of spectrum (alias components) which are shown hatched and extend well within the wanted region of the band, i.e. 0 – 5·5 MHz.

Fig. 5(*c*) thus represents the spectral characteristic of the signal emerging from the sensor. If it is to be resampled at a different frequency (that of the subsequent digital processing) it must be low pass filtered to remove the components above the required video bandwidth.

3.1. Efficiency of removal of frequency components at the sensor sampling frequency

Assuming that the low pass filter defines the bandwidth of the wanted information by its –3 dB point, a criterion can be deduced to define the necessary characteristics of such a filter. With reference to Fig. 5(*d*) we see that:–

$$f_s \geqslant 2f_b + \Delta f_{(-3 \text{ to } -45)\text{ dB}}$$

where f_s = sampling frequency of the second sampling process (i.e. the digital processing).

f_b = required bandwidth (usually 5·5 MHz)

$\Delta f_{(-3 \text{ to } -45)\text{ dB}}$ = frequency difference between the –3 dB and –45 dB points of the filter.

The figure of –45 dB is tentatively suggested here as a reasonable target for the degree of alias suppression necessary, based upon past experience with the visibility of interfering signals.

It should be noted that in this relationship, only the resampling frequency f_s is involved, not the sampling frequency of the sensor. However, this relationship only gives the characteristics of a filter designed to remove unwanted frequency components arising out of the energy distribution in the sampled scene, it does not take into account spurious frequencies caused by for example, clock pulse breakthrough occurring in the sensor.

This breakthrough arises because large voltage levels of clock pulse (of the order of 15V) are usually used to drive the internal scanning circuits in a sensor. In CCD's this breakthrough can occur at the sampling frequency and at multiples of it and in some scanning arrangements it can even occur at half the sampling frequency.

The level of breakthrough is always unpredictable, but if, for example, it occurred at the sampling frequency f, then the second sampling process, at a frequency f_s would give rise to a beat frequency of $f_s - f$. Under these circumstances it might well be necessary to supplement the low-pass filter response with a notch filter at f and possibly also at some of its harmonics.

It is clear that there are no theoretical obstacles to resampling the output at a frequency which is different from the sampling frequency of the sensor, the problem is purely one of filter design optimised for the particular type of sensor and the sampling frequencies used.

3.2. Alias components caused by the sampling structure of the sensor

A more difficult question to resolve is the tolerable level of alias components produced by the sensor itself as a result of trying to resolve an optical image containing higher resolution than the sensor can reproduce. These are the alias components illustrated in Fig. 5(*c*).

With a larger number of elements in the sensor, i.e. with a higher value of f_s, there will be less likelihood of serious interference from such components but this is a parameter over which there is very little control, since it depends on the quality of the camera optics, it being virtually impossible to attain an idealised sharp cut spatial filter for the optical image.

For this reason the broadcaster is tempted to ask for very high resolution, well in excess of the Nyquist minimum,

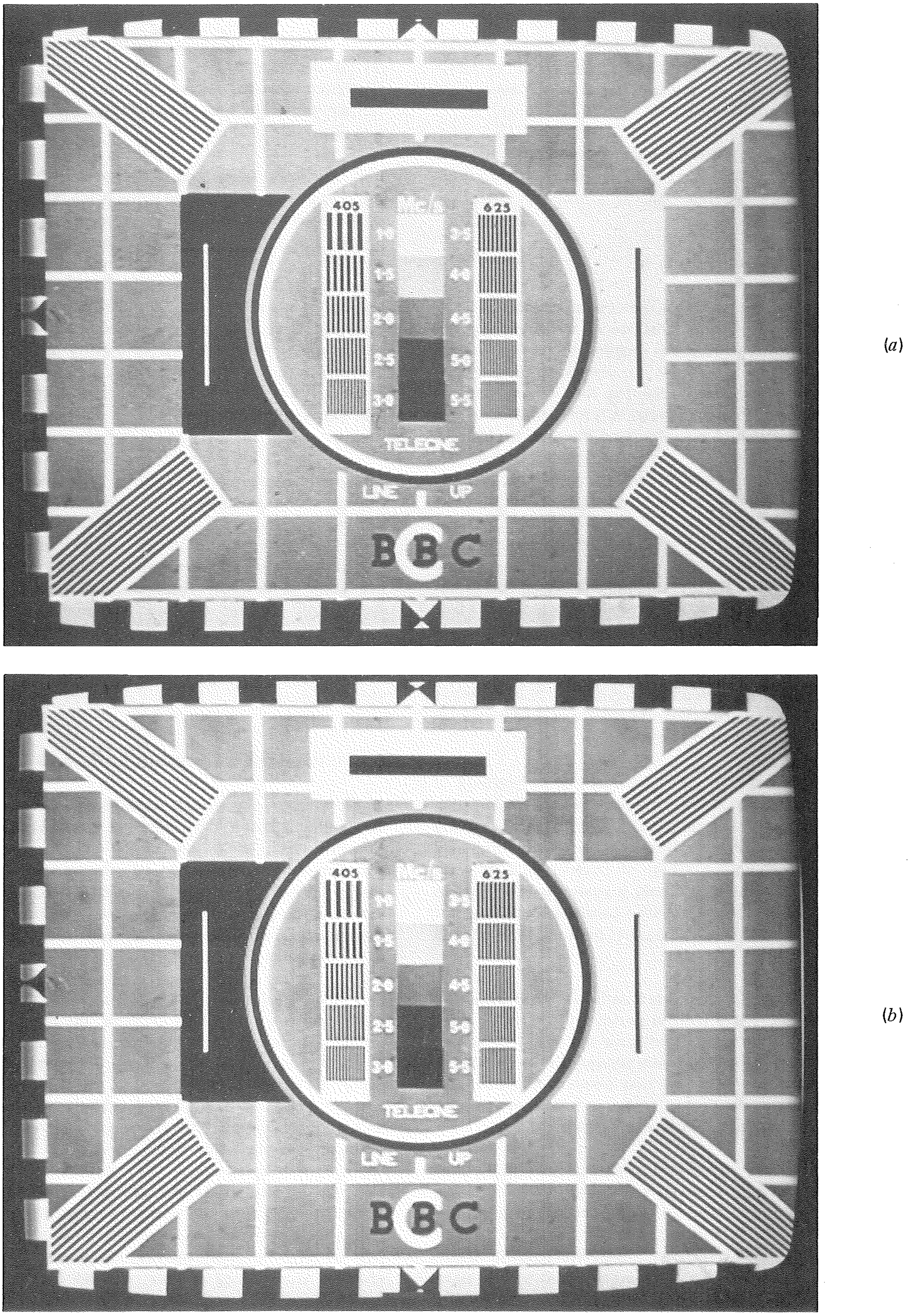


Fig. 6

(*a*) Test Card C as reproduced from film using the 1024 element sensor
(*b*) Test Card C as reproduced from film using the 1024 element sensor as a 512 element sensor

purely in order to minimise the danger of encountering alias components. The sensor manufacturer, on the other hand, will have achieved a great deal if he can even reach the Nyquist minimum resolution.

A compromise between alias components and resolution will have to be found, but the nature of this compromise will only become clear as a result of subjective experience.

3.3. Experimental results so far

Whilst experience with high resolution devices is of necessity limited at present, line sensors are being used for scanning film, using continuous motion of the film to scan the image vertically.[3,4] Whilst it is dangerous to generalise the results obtained from scanning film to the case of television cameras using area arrays, it is nevertheless helpful to identify the order of magnitude of the alias problem as applied to film. It is in any case felt that telecine machines using line sensors may well provide an attractive basis for the design of future generations of telecine.

A 1024 element line sensor is at present under investigation to assess its suitability for telecine use. One feature which makes it useful for investigations into alias formation is that the 1024 elements are actually two groups of 512 elements physically interleaving with each other and having distinct outputs. Thus the sensor only becomes a 1024 element sensor when the two outputs, with their interleaving sample streams are added together. It is therefore possible to view any scene simultaneously as a 512 element picture and a 1024 element picture.

The 1024 (or 512) elements have to be scanned in 52 μS, so the corresponding data rates are 19·69 MHz (or 9·85 MHz), thus the potential Nyquist bandwidths are 9·85 MHz (or 4·92 MHz). Thus it is possible to compare a comfortably oversampled signal of potentially 9·85 MHz bandwidth with a system of only just enough elements to give a reasonably sharp 4·92 MHz bandwidth picture, but with no margin of protection against the formation of alias components.

Fig. 6(*a*) and (*b*) show a test card as viewed under the two conditions. There is little obvious difference in resolution between the two pictures, but the beat frequencies on the 512 element image are very obvious in the frequency bars. This shows that the frequency bars, being non sinusoidal, have a great deal of energy at harmonics extending well outside the bandwidth of 4·92 MHz.

The subjective impression gained when viewing programme material was, however, somewhat different. The alias components were seldom visible and never objectionable even to engineers well accustomed to seeing effects of this type. Although subjective tests were not formally carried out it can provisionally be estimated that present day 16 mm film is unlikely to contain high frequency components of sufficient energy to be troublesome in a marginally sampled system. This conclusion is not, however, valid for 35 mm film and is, indeed, subject to confirmation by future work involving properly conducted subjective tests.

The above work does not throw a great deal of light on the desirable future resolution of solid state sensors in television cameras, where the optical image is likely to contain far more high frequency energy than that of 16 mm film.

The only experimental evidence so far available as to the effect of sampling a real scene is the vertical sampling of all television images. Alias components produced by this process are commonly seen, but have become accepted as an unavoidable by-product of the scanning process. By its very nature, it is sampled at the Nyquist limit because no attempt is made to prefilter the scene or to subsequently filter the vertical samples. A conventionally scanned television picture is thus probably a fairly good indication of the alias problems likely to be seen on a marginally sampled sensor output, but with the alias components then extended into two dimensions.

It should be added that in many of the tests carried out on the pictures produced by line sensors, digital processing of the signal has been used. If, for example, it is desired to convert the essentially sequentially scanned output of this type of film scanner into an interlaced sequence, digital processing involving storage must be used. On other occasions, gamma correction has also been applied digitally. At no time has the sampling frequency of the digital processing been linked to that of the sensor; and in every case a simple low pass filter has been sufficient to remove potentially harmful frequency components from the first sampling process.

4. Conclusions and recommendations

This report has sought to show that it is both undesirable and unnecessary to attempt to link the sensor sampling structure with that of subsequent digital processing. The two sampling processes can be independent provided that care is taken in the design of the filters necessary to remove components arising from the sensor sampling process. A simple relationship has been derived to act as a guideline in the design of such filters.

It is felt that the choice of sampling frequency for the sensor must above all be dictated by the need to avoid serious alias components arising out of the unavoidable lack of prefiltering of the optical image, and not by the needs of digital distribution and processing, which in the interests of cost reduction and bandwidth reduction will tend to use the minimum acceptable clock frequencies combined with various forms of prefiltering.

At present it is not possible to make a specific recommendation for the optimum number of elements in a solid state sensor for use in television cameras owing to the lack of experimental evidence, but experience with film scanning would suggest that between 500 and 600 horizontal elements would probably produce visible aliasing, comparable with that produced by the existing vertical structure of the television system. On the other hand 1000 elements or so is almost certainly unnecessarily high. It therefore seems likely that acceptable results will be achieved by sensors having between 600 and 1000 elements in the line direction.

5. References

1. SEQUIN, CARLO H. 1973. Interlacing in charge-coupled imaging devices. *I.E.E.E. transactions on electron devices*, Vol. ED–20, No. 6, June 1973, pp. 535 – 541.

2. LE COUTEUR, G.M. 1976. The potential for solid state image sensors in broadcasting. Paper presented at IBC 76, London, September 1976.

3. WRIGHT, D.T. 1973. Solid state sensors: the use of a single dimension 512 element array for film scanning. BBC Research Department Report No. 1973/32.

4. LE COUTEUR, G.M. 1976. Solid state sensors: improvements in signal processing techniques. BBC Research Department Report No. 1976/4.

Appendix

Outline description of the two principal methods of scanning Charge Coupled Devices

1. Interline transfer

With reference to Fig. 1(*a*) it can be seen that the light sensitive elements are arranged in columns interleaving with columns of storage elements. The storage elements feed into a horizontal output register.

Integration of light takes place for the duration of a picture. At the end of this period, during the field blanking interval, every other light sensitive element in each column is made to transfer its charge into the neighbouring storage element, the storage elements being shielded from the light. (The remaining light sensitive elements contain information for the interleaving field and are not used until the subsequent field blanking interval.)

During the course of the ensuing field, the video information in the storage columns is clocked line by line into the horizontal output register, and the contents of each line are read out of this register during the active line period.

Whilst this arrangement provides a true interlaced scanning sequence, the sensitivity is impaired by having half the available illuminated area shielded for use as storage.

2. Frame transfer

With reference to Fig. 1(*b*), it can be seen that in this arrangement the light sensitive areas and storage areas are separated into two adjoining areas, with the horizontal output register below the storage area.

Both sets of elements, light sensitive and storage should be regarded as being in vertical columns, each pair of columns comprising a continuous shift register.

Light integrates in the light sensitive area for a field period, and then during the field blanking interval the accumulated charge is shifted rapidly down into the shielded storage area. During the ensuing field the video in the storage area is clocked line by line into the horizontal output register and read out during each active line.

Interlace is achieved by varying the centre of the light sensitive elements in alternate fields by adjustment of potential well shape. Although the interlace thereby achieved is fairly satisfactory, the vertical aperture is wider than in the corresponding interline transfer case.

SMW/DS

Printed by BBC RESEARCH DEPARTMENT, Kingswood Warren, Tadworth, Surrey, KT20 6NP